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Abstract:

The U.S. Department of Energy has a program to develop fuel cell technology for automotive applications. For maximum efficiency, a fuel cell system requires a compact, lightweight, and highly efficient air compressor to provide a stream of clean air to the fuel cell stack. Meruit, Inc., is developing a turbocompressor for this application. Journal and thrust air bearings are two critical components of the turbocompressor that require low friction and excellent wear resistance. These components were coated with Argonne's new low-friction amorphous carbon coating and tested in an air bearing test rig. Results to date show that the coating provides the required friction reduction, as indicated by reduction in time to lift-off of the radial journal bearing during cyclic start/stop testing. The coating also prevented wall climbing which can cause bearing instability. In spite of a slight inbalance in the coated test bearing, wear on the coated surface, which occurred by polishing and mild abrasion, was at an acceptable level.

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Introduction:

The U.S. Department of Energy (DOE) in conjunction with industry under the Partnership for the New Generation of Vehicles (PNGV) program is currently developing fuel cell technology for transportation applications. Successful commercialization of this technology will result in significant reduction of fuel consumption and dependence on oil, especially foreign oil. It will also substantially reduce exhaust emissions, thereby protecting the environment and eliminate health hazards associated with automotive engine emissions. The proton-exchange membrane (PEM) fuel cell system is the technology of choice for the DOE-PNGV program. The PEM fuel cell stack requires a stream of compressed clean air for efficient operation. This is to be supplied by a compressor/expander air management system. There is thus the need for a light-weight, compact, and highly efficient compressor/expander system. Indeed, it is now recognized that the performance and overall efficiency of the entire fuel system depend on the air management subsystem [1].

Because, no off-the-shelf compressor/expander technology is available to meet the stringent requirements for this application, DOE initiated a program to develop such technology for the PEM fuel cell system. Several contractors are working on various compressor/expander systems that can meet the weight, size, efficiency, and cost requirements as set by DOE. One of the contractors, Meruit, Inc., has designed and built a prototype of a novel radial journal and thrust air bearings for use in a turbocompressor [2,3]. For the fuel cell application, air bearings are preferred, because oil or grease lubricant can contaminate the fuel-cell stacks.

For an air bearing under normal operation, a high-pressure air film separates the surfaces of its radial journal and thrust components. However, during start-up or shut-down, the bearing component surfaces will make contact with, and slide against each other. Under such condition, surfaces with low friction and wear resistance are needed. The low-friction amorphous carbon coating (called NFC) developed at Argonne was thus evaluated as a potential material for protecting the air-bearing component surfaces. A Laboratory bench top screening test with a thrust-washer contact configuration showed that the coating can reduce the friction of 440C stainless steel surface by a factor of 4 and reduce the wear rate by a factor of 10 [4]. Other tests also showed that the coating can substantially increase the scuffing or seizure resistance of steel surfaces under severe contact conditions [5].

Based on the positive laboratory test results in terms of friction and wear reduction, as well as seizure prevention, the next step is the evaluation of the coating in an air-bearing rig test. Journal air-bearing components were coated with Argonne's amorphous carbon coating and tested for durability. This paper presents the results of this evaluation.

Experimental Details:

Coating:

An air-bearing rotor fabricated from hardened stainless steel PH17-4 was supplied to Argonne by Meruit, Inc., for coating. The coating was deposited by RF-plasma-assisted chemical vapor deposition (PACVD) process. To ensure good adhesion of the coating, the rotor surface was sputter cleaned in an Ar plasma for 30 min, and a 50-nm-thick Si bond layer was deposited afterwards. The amorphous carbon coating was deposited by chemical vapor deposition (CVD) from a plasma created by a gas mixture of 50% methane and 50% hydrogen. Thus, the coating is a hydrogenated variation of amorphous carbon coating. Details of the coating depositions and the coating properties have been previously described [6,7]. A coating of about 2.5-μm thickness was deposited on the rotor.

After coating, several dimples were created on the air-bearing rotor, as shown in Figure 1, by a Calowear test method. This common method used for measurement of coating thickness, involves loading a rotating ball of known diameter against the coated surface. By measuring the dimple dimensions before and after testing, the amount of linear wear in the coating can be calculated as:

$$W_L = \frac{1}{2}\left\{\left[\sqrt{(4R^2-d^2)}\right] - \left[\sqrt{(4R^2-D^2)}\right]\right\}$$

where R is the radius of curvature of the dimple (15 mm in the present case), D is the initial dimple diameter before the test, and d is the dimple diameter after the test.

Bearing Test:

The journal air-bearing rotor coated with amorphous carbon was tested on an air-bearing test rig designed and constructed by Meruit, and located at FD Contours (Costa Mesa, CA). Figure 2 shows some components from the air-bearing test setup, including the coated rotor shaft. The bearing is driven by a turbine mechanism, powered by compressed air supplied from a commercial air compressor. Circuitry control allows for automatic cyclic on-and-off power to the turbine. Proximity sensors and tachometers at various locations provide measurements and information on the location and speed of the air bearings during the test. Details of the air-bearing test rig and its operation are given in a report by Meruit [8].

When the air bearing is operating at normal speed, no contact occurs between the floating rotor shaft and the journal. Under such conditions, wear or damage to the bearing is not expected. At start-up, however, a sliding contact occurs between the bearing rotor and the journal. Similarly, at shut-down, sliding contact will occur between the bearing and the journal until it coasts to a stop. These sliding contacts at start-up or shut-down are what limit the endurance or durability of the bearing.

Consequently, the test protocol used in this study focused primarily on the start-up and shut-down stages. The test procedure involves cyclic starts and stops, reaching a maximum speed sufficient only to float the rotor. The lift-off and landing times and speed were detected by the proximity and tachometer probes. Tests were conducted for a selected number of start-stop cycles, then the surface of the coated rotor was inspected, the dimple dimensions were measured, and the salient features on the bearing surfaces were characterized by optical microscopy. This characterization provides information on the wear mechanisms of the coating. Some tests were conducted with uncoated steel bearing and two different low-friction polymeric material journals, namely, Vespel and Delrin. Because the steel bearings for these tests, have no dimples, a wear measurement could not be made on the uncoated steel bearing rotor.

Results and Discussion:

In the air-bearing test rig used for this study, analysis and dynamic test results have shown that a high friction coefficient between the bearing rotor shaft and the journal surfaces can result in wall climbing at start-up. Such an event prevents smooth sliding and quick floating of the air bearing. Figure 3a shows the speed at lift-off for the three material pairs tested in the air bearing. Note that a test combination of uncoated steel-on-steel bearings failed to run due to excessive wall climbing and the resulting dynamic instability. The lift-off speed for the NFC-coated rotor shaft running against an uncoated steel journal is about 1000 rpm, which is much lower than the lift-off speed for the tests with the uncoated steel rotor and Vespel or Delrin journals. This low speed is due to the lower friction coefficient of the NFC-coated bearing and steel journal combination. As expected, the time to lift-off follows the same trend as the speed to lift-off (Fig. 3b).

Figure 4 shows the variation of the linear wear (W_L) with the number of start/stop cycles for various dimples on sides 1 and 2 of the NFC-coated, air-bearing rotor shaft. In general, more wear occurred on side 1 than side 2. This finding suggests some imbalance in the bearings such that one side lifted off or touched down before the other side. Less wear is expected on the side that lifted off first, because the duration and speed of sliding will be less. Wear data of the present study suggest that side 2 lifted off first.

On both sides of the air bearing, it appears that the linear wear was approaching a steady value for most dimples. On side 1, the wear after 4000 cycles was about the same as after 2000 cycles in six of the eleven dimples (Fig. 4a). The highest amount of wear, about 1.5 μm of the original 2.5 μm, occurred in three of the dimples. The wear in most of the dimples on this side of the rotor shaft was about or less than 1 μm. On side 2, except for two dimples, the wear in most cases was below about 0.5 μm. The rapid wear in the two peculiar dimples occurred during the last test between 2000 and 4000 cycles. The observed trend in the linear wear indicates that the run-in process, during which a higher wear rate is expected, is almost complete for the air bearing. Once run-in is complete, little or no further wear is expected under normal operating conditions. Because about 1 μm of the coating is still left in the location with the most wear, and the run-in is almost complete, we concluded that the NFC coating may be durable enough to reach the desired 100,000 start/stop cycles. Only further testing, however, can determine the actual durability of the NFC coating in the air bearing.

Examination of the NFC-coated bearing surface after testing showed that occurred primarily by polishing and mild abrasion, even in the worst case. Figure 5 shows the optical micrograph of one of the dimples with the most wear (dimple 1-9) after 250 and 4000 cycles. There is clear evidence of polishing wear after 250 cycles, but the original grinding marks are still clearly apparent (Fig. 5a). Note that the coating process did not change the surface finish of the bearing. The coating surface shown in Figure 5a is almost a mirror image of the underlying material. After 4000 cycles, however, abrasive wear is visible, with fine scratches and grooves running in the sliding direction (Fig. 5b). Most of the original grinding marks have worn away. In locations with little wear, such as dimple 1-3, the wear mode consists of very mild polishing of the asperity peaks. All the grinding marks are still present even after 4000 cycles. Indeed, little or no difference can be seen on the surface after 250 (Fig. 6a) and 4000 (Fig. 6b) cycles.

Although no quantitative measurements were made of the wear in steel bearings used in the tests with Vespel and Delrin journals, excessive wear was observed in these polymeric materials. This resulted in increased clearance between the bearing and the journal, which over time will compromise the overall durability and performance of the air bearing. In addition, accumulation of wear debris from the polymer journal may interfere with the smooth running of the bearing. Because the polishing wear mode is dominant in the NFC-coated bearing, minimal and non-detrimental debris is expected. Based on the results of the air-bearing test to date, the NFC coating is a good candidate and perhaps a needed enabling technology for successful operation of a turbocompressor air bearing for the fuel cell application.

Summary:

The performance of Argonne's amorphous carbon coating on a radial journal air bearing being developed for turbocompressor in fuel cell systems was evaluated in an air-bearing test rig by following a start/stop cycling test protocol. Test results showed that the coating provided the low friction interface required for the bearing shaft and journal contact. Without such low friction, excessive wall climbing occurs, resulting ultimately in dynamic instability. Because of its low friction, the bearing with amorphous carbon coating achieved lift-off and touch-down speed of about 1000 rpm, substantially lower than the value of about 6000 rpm for the Vespel and Delrin polymeric material journals. By 4000 cycles, the run-in of the coated bearing was apparently complete, after which little or no further wear is expected. Observation of unequal wear on the two sides of the bearing suggests it is not balanced. The fact that the coating enables an unbalanced bearing to run without a catastrophic failure is a significant positive attribute of the coating. The wear mechanism in the coating consisted of polishing and mild abrasion. The debris generated by such a mechanism is not expected to adversely affect the performance of the bearing.

Acknowledgment:

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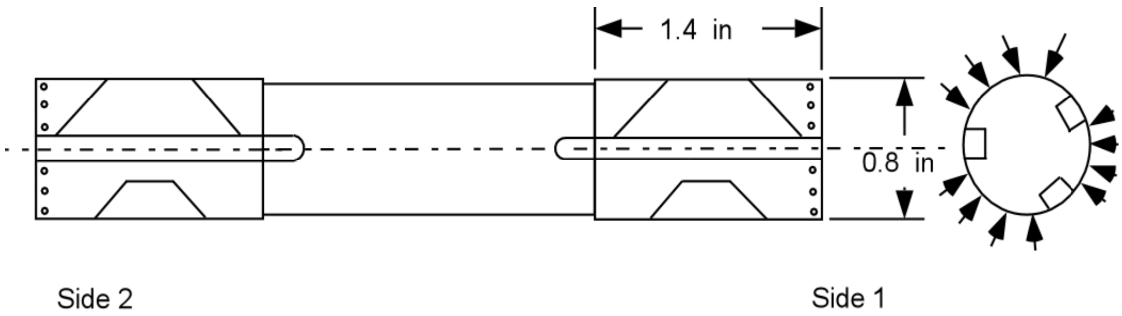


Figure 1: Schematic of coated air bearing showing the location of dimples (arrows around bearing)

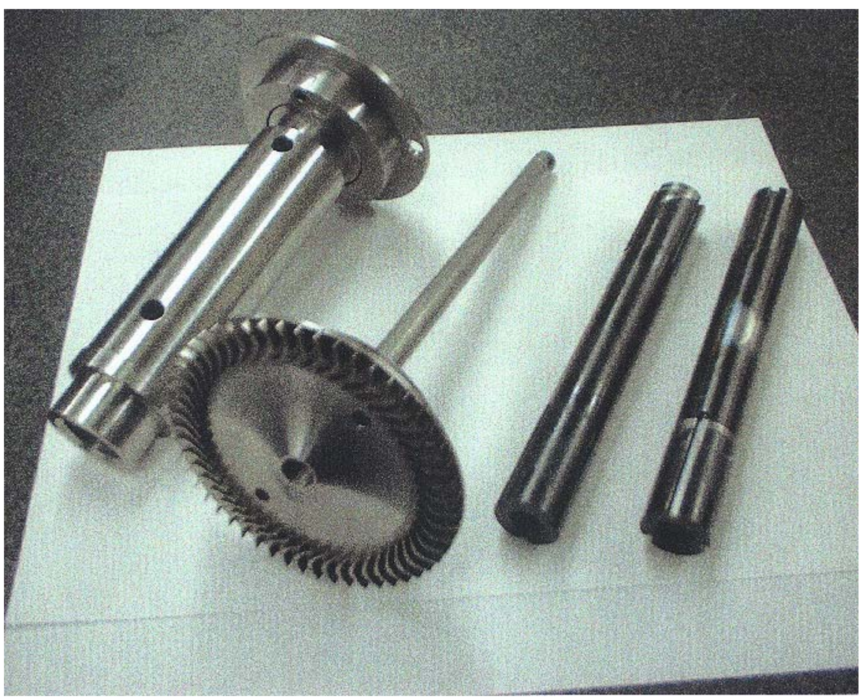
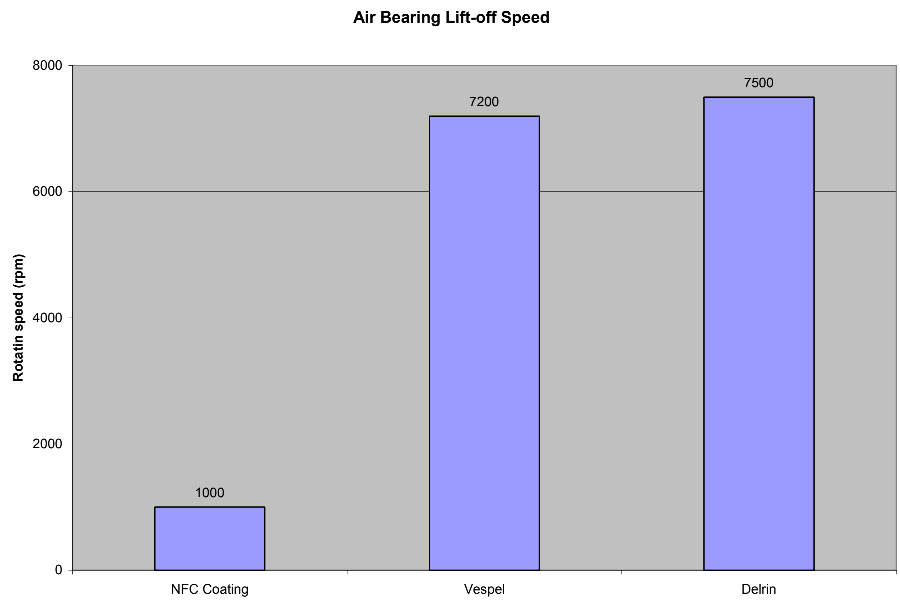
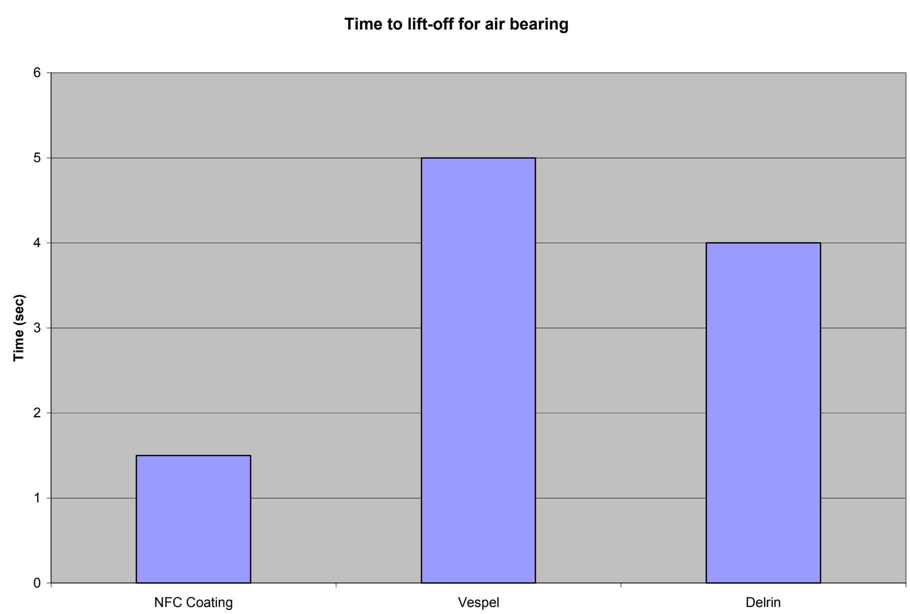


Figure 2: Some components in air-bearing test rig, including coated air-bearing shaft

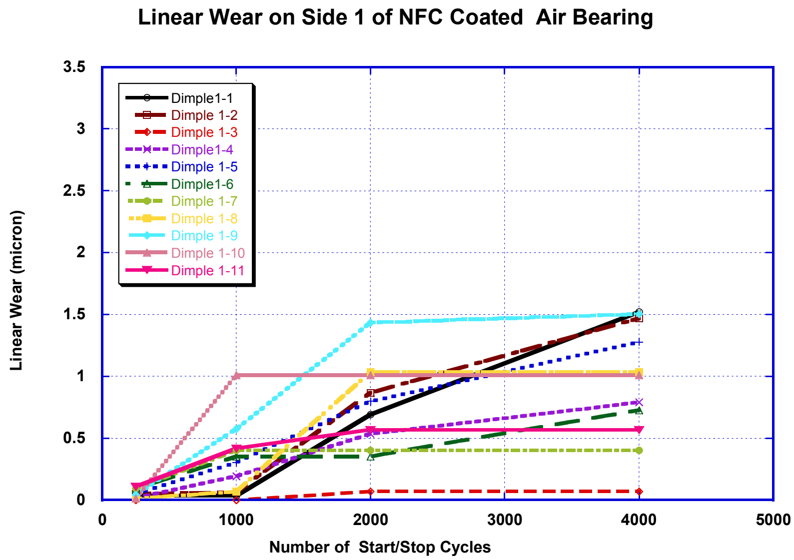


(a)

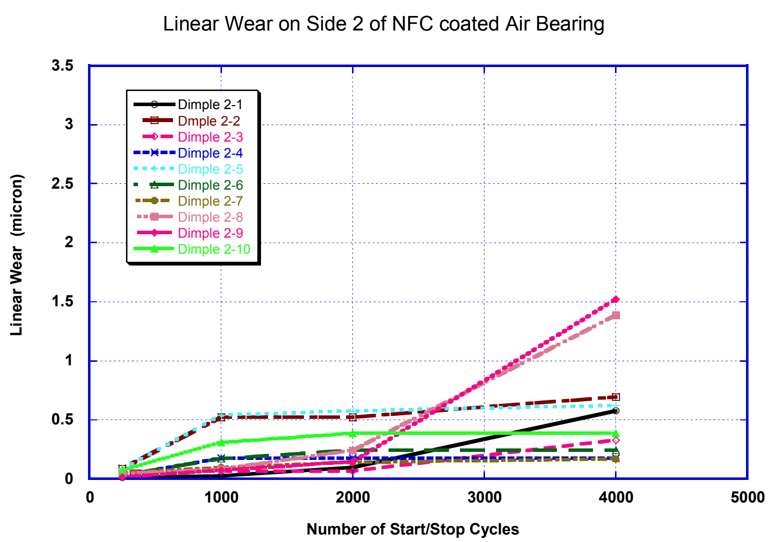


(b)

Figure 3: (a) Speed at bearing lift-off and (b) Time to bearing lift-off

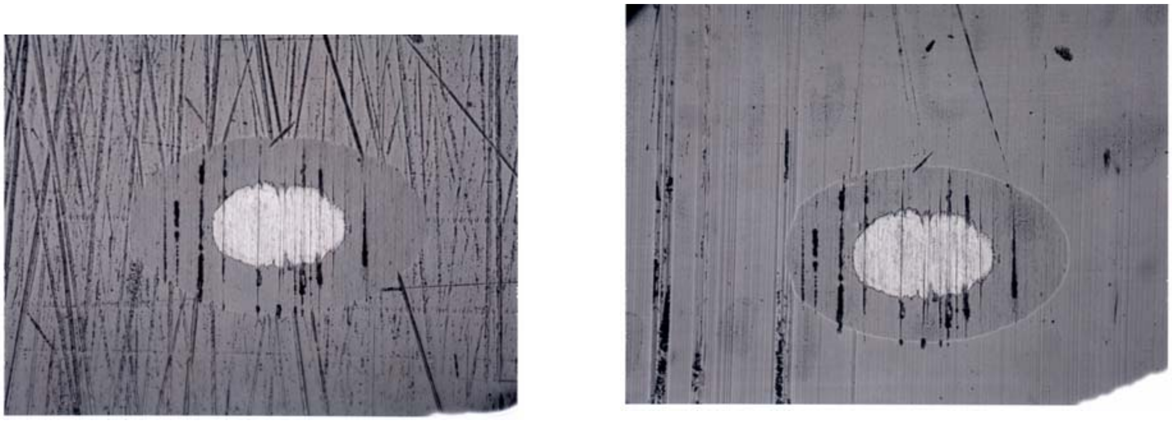


(a)



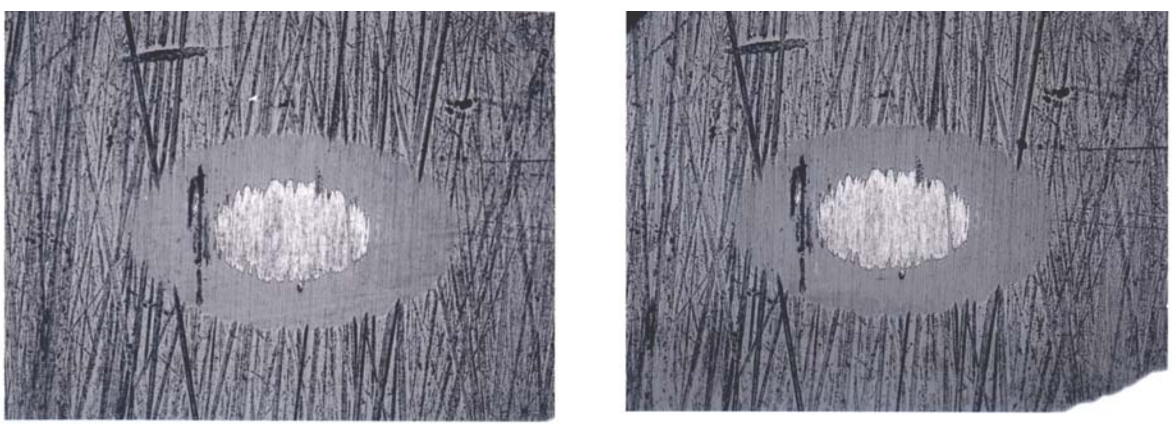
(b)

Figure 4: Variation of linear wear at the dimples with number of start/stop cycles: (a) side 1, and (b) side 2.



(a) (b)

Figure 5: Optical micrograph of dimple 1-9 after (a) 250 cycles and (b) 4000 cycles



(a) (b)

Figure 6: Optical micrograph of dimple 1-3 after (a) 250 cycles and (b) 4000 cycles